



Beyond Einstein: From the Big Bang to Black Holes

ST7 and LISA Colloid Microthruster Technology

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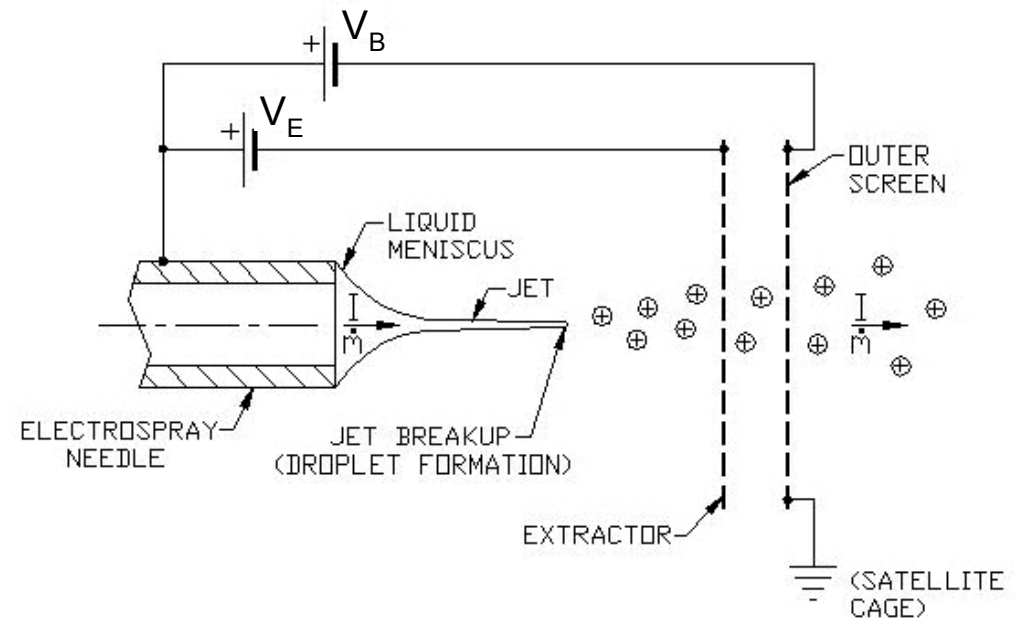
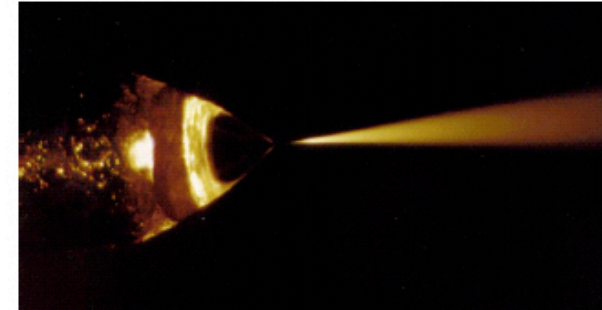
Colloid Electrospray Microthrusters

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- A balance between electrostatic and surface tension forces produce an **electrospray** of ions and droplets
- Colloid Thrusters use the electrospray to produce stable, precise thrust in two stages: extraction and acceleration

$$\text{Thrust} \propto I_B^{1.5} \cdot V_B^{0.5}$$

- In this design, current and voltage are controlled independently, and the specific impulse is determined by the voltage of the emitter electrode (beam voltage, V_B)
- Precise control of I_B ($\sim \mu\text{A}$) and V_B ($\sim \text{kV}$) facilitates the delivery of micro-Newton level thrust with $< 0.1 \mu\text{N}$ precision
- The exhaust beam is a positively charged stream that must be neutralized by a cathode/electron source to mitigate spacecraft charging

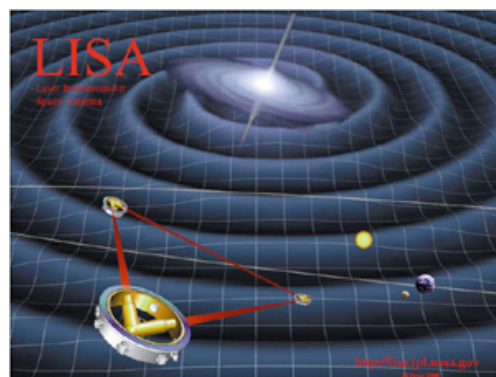
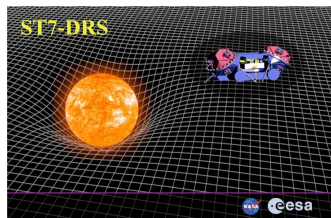
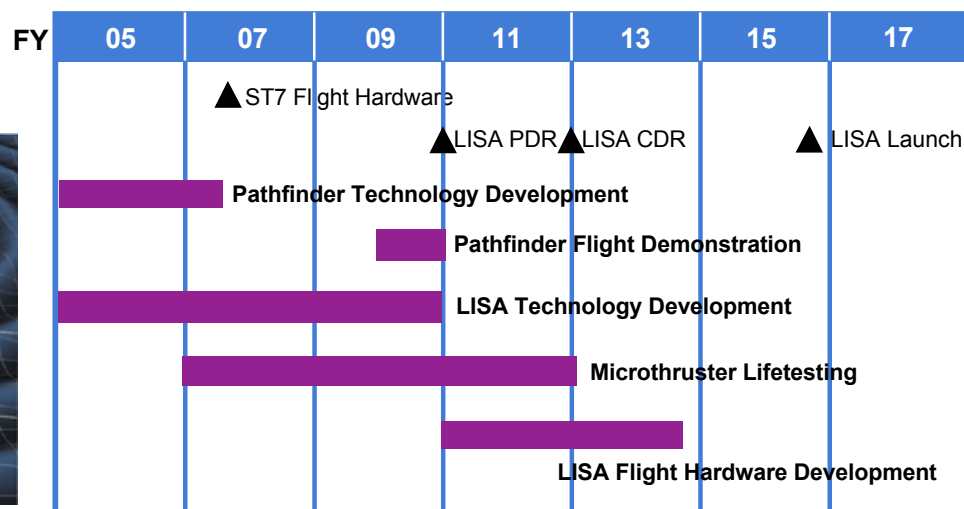
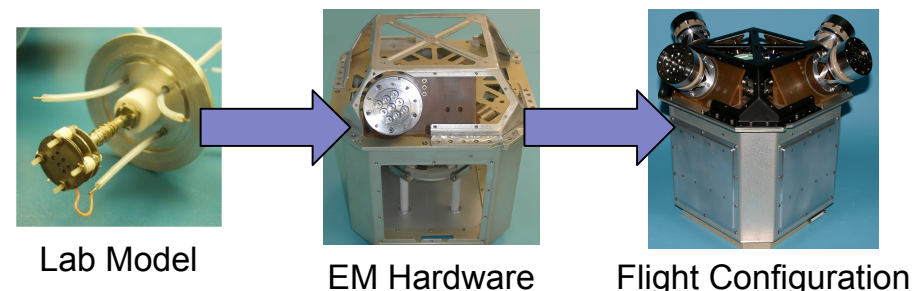
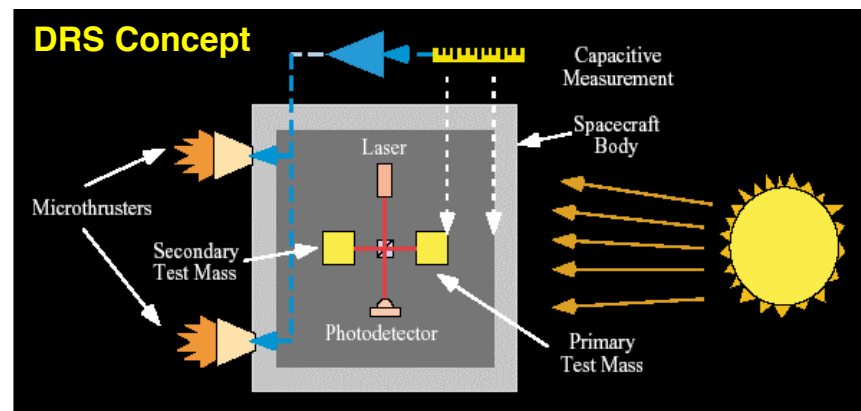


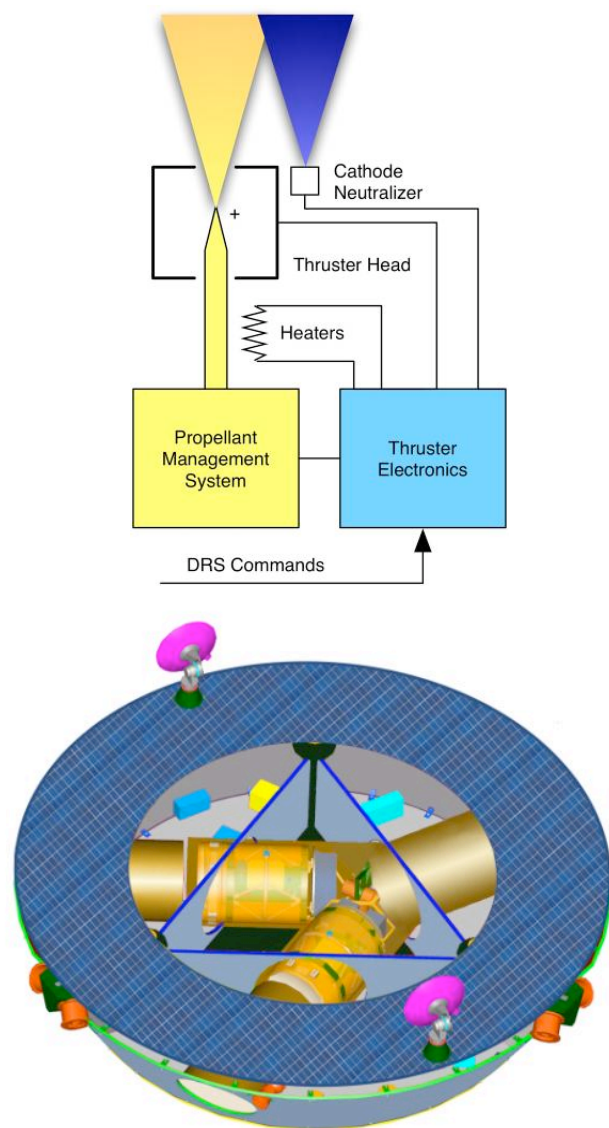
- 🪐 LISA Colloid Microthruster Technology Development
 - ST7 and LISA Requirements
 - LISA Technical Challenges
- 🪐 Progress on ST7 for LISA Pathfinder
 - ST7 System Overview and Flight Hardware Fabrication
 - Component and System Performance
- 🪐 Thruster Lifetime Testing
- 🪐 Plume Measurements and Models
- 🪐 Summary:
 - **We are building flight hardware and will demonstrate the technology on ST7, while for LISA we need to focus on improving thruster lifetime**

Drag-free requirements for LISA demand a new microthruster propulsion technology

- Disturbance Reduction System (DRS) requires force noise $< 0.1 \mu\text{N}/\sqrt{\text{Hz}}$ for a minimum of five years of continuous operation
- JPL is responsible for LISA colloid microthruster technology development over the next four years, focusing on the CMNT developed by Busek to be demonstrated on ST7-DRS and LISA Pathfinder
- ESA developing two types of FEEP microthruster technology and will also demonstrate one of them on LISA Pathfinder

LISA Pathfinder (LPF) and Space Technology 7 (ST7) Missions will develop the technology to the flight level and demonstrate microthruster performance on-orbit





Baseline LISA Microthruster Architecture is an electrospray micronewton thruster

- Colloid and Field Emission Electric Propulsion (FEEP) thrusters are leading candidates
- Sub-systems include the thruster head, cathode neutralizer, propellant management system, and thruster electronics regards of electrospray type

Three clusters of two thrusters equally spaced around the spacecraft will balance any disturbance on the spacecraft, mainly solar photon pressure

The thruster head and electronics design will follow from ST7 and LISA Pathfinder flight demonstrations while the propellant management system will need to be scaled to meet LISA mission duration requirements

Requirement	ST7 Value	LISA Value
Thrust Range	5 - 30 [*] μ N	4 - 30 [‡] μ N
Thrust Precision	< 0.1 μ N	< 0.1 μ N
Thrust Noise	< 0.1 μ N/ $\sqrt{\text{Hz}}$	< 0.1 μ N/ $\sqrt{\text{Hz}}$
Operational Lifetime	2,200 hours	55,000 hours
Duration for Propellant Storage	3 months	8.5 years
Total Impulse	200 Ns for sun facing thrusters, 300 Ns for sun apposing thrusters	18,000 Ns over all thrusters, i.e. 3,000 Ns per thruster for six thrusters
Exhaust Contamination on Spacecraft	< 0.1 μ g/cm ²	TBD

Notes (*): LISA Pathfinder requires higher maximum thrust (100 μ N) to maintain L1 orbit

(‡): Maximum thrust is determined by tip-off requirements and could change

🌀 This leads to the following common microthruster performance requirements:

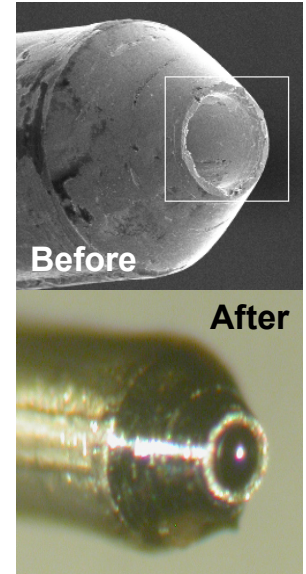
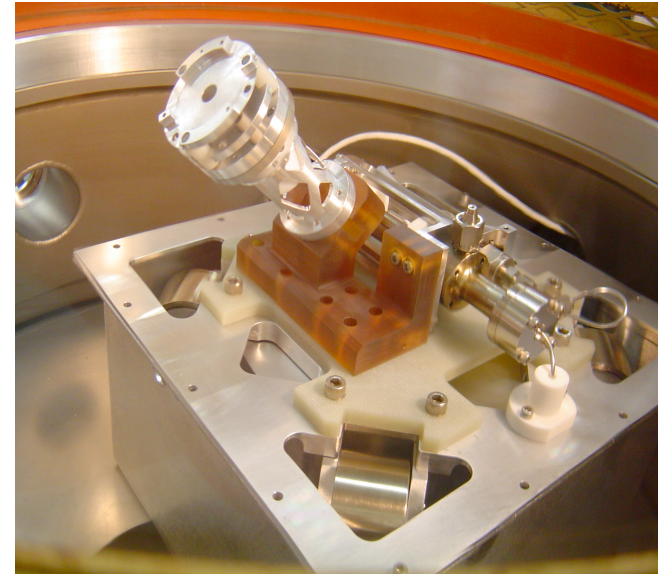
- Tight control of current and voltage (thrust), plume shape (S/C contamination), and beam charge neutralization
- Unique thrust stand and vacuum test facilities capable of resolving sub- μ N forces and measuring plume properties over a large volume

🌀 For LISA requirements, mainly a change in lifetime: 55,000 hours of continuous operation (25x lifetime) and 8.5 years worth of propellant (10x total impulse)

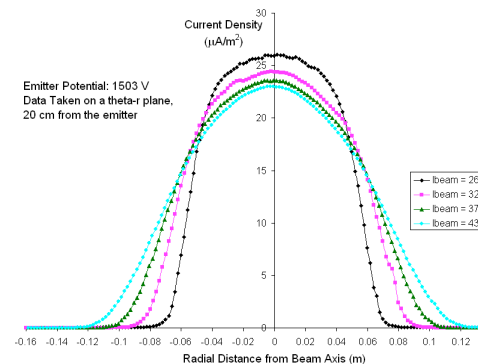
- Compared to LISA Pathfinder or ST7-DRS design, LISA requires a larger propellant tank and perhaps a minimum specific impulse (exhaust velocity)
- Demonstrating and verifying lifetime requires unique long-duration test facilities and development of verified physics-based models for thruster operation

Challenges for Colloid Microthruster Technology Development

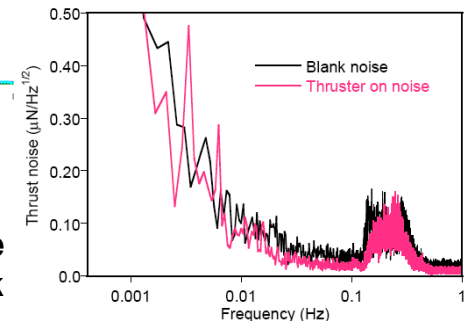
- Performance: **Demonstrated by ST7-DRS**
 - Models and measurements have verified almost all requirements to date
 - Thrust noise at low frequencies with multiple emitters is last remaining measurement
 - Focusing electrodes could increase specific impulse, thrust range, and reduce contamination
- Contamination: **Demonstrated by ST7-DRS**
 - Measurements and models have verified almost all requirements to date
 - Relatively few measurements remaining, completed by end of Phase A, spacecraft interaction model complete by end of Phase B
- Lifetime (55000 hours): **LISA Focus**
 - Longest test to date of a single emitter is 3400 hrs at Busek (four of these tests have been completed)
 - For LISA we have already identified potential lifetime issues:
 - Emitter clogging (electrochemistry, particulates)
 - Bubble formation (propellant contamination)
 - Overspray (excess propellant onto electrodes)
 - Solutions require fundamental understanding of the long-term emission processes



Busek 3400 hour Lifetest



Plume Measurements / Characterization at JPL



Thrust Precision / Noise Measurements at Busek



Technology Development Strategy



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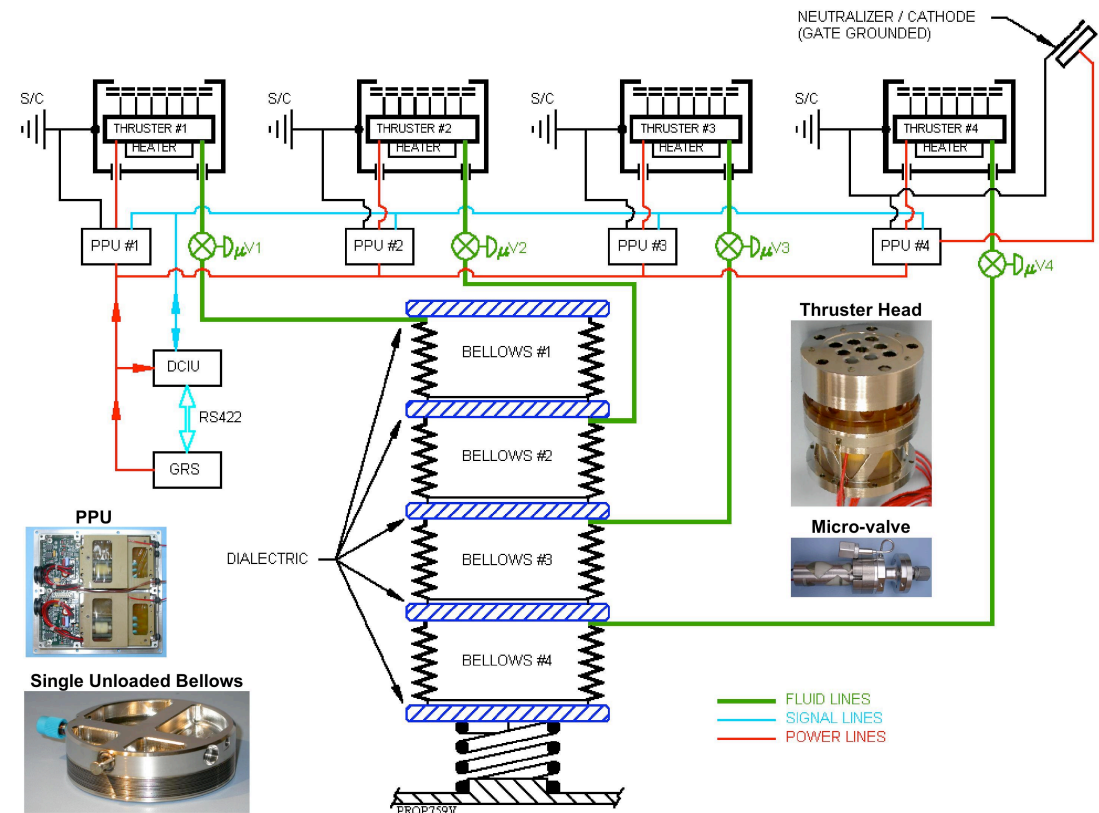
- 🚀 ***LISA Microthruster Technology Development will focus on Lifetime***
 - Have two options developed in parallel: Colloid and FEEP microthrusters, that will both be tested on LISA Pathfinder
 - Performance and contamination will be demonstrated as best as can be tested on the ground and in flight on LISA Pathfinder
 - Only change flight design where necessary for lifetime considerations and have well-defined developmental gates and milestones to monitor progress
- 🚀 Thruster life will be determined by physics-based models validated by laboratory experiments and “short term” wear testing
 - Duration of formulation phase does not permit 5 years of continuous testing by end of technology development program
 - Requires multiple short duration (1000-4000 hr) tests at multiple facilities to identify failure mechanisms and develop detailed models of physics behind operation and failure (much of this completed during ST7 activities)
 - One long duration lifetest (> 8000 hr) on LISA prototype thruster will be complete by PDR to verify models, continuing on through LISA CDR
- 🚀 Technology off-ramps include modifying drag-free control bandwidth to accommodate larger thrust noise and increasing number of cold spares to accommodate reduced thruster lifetime, if necessary



ST7 Microthruster System Architecture

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Cluster with 4 Thruster Systems



- ST7-DRS has 2 clusters with 4 thrusters per cluster
- All 8 thruster systems are identical
- There is one DCIU and neutralizer per cluster
- Thrust range: 5-30 μN from each thruster head

A single thruster sub-system includes:

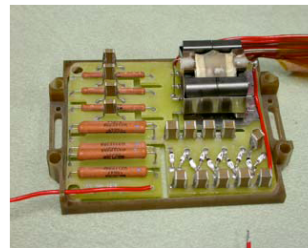
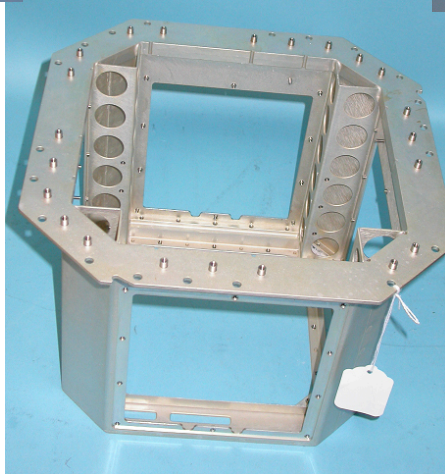
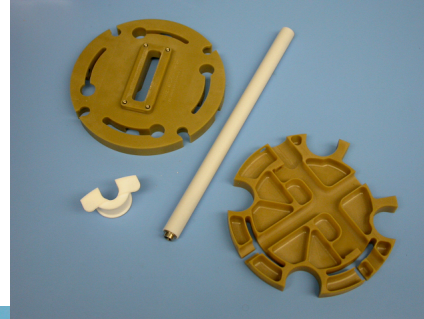
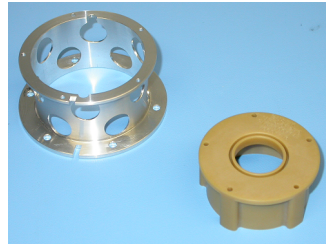
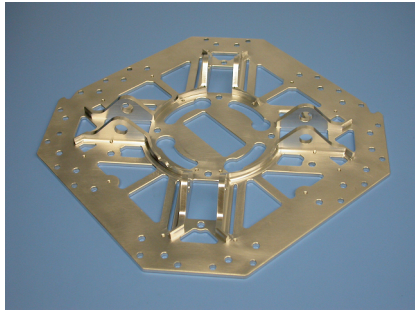
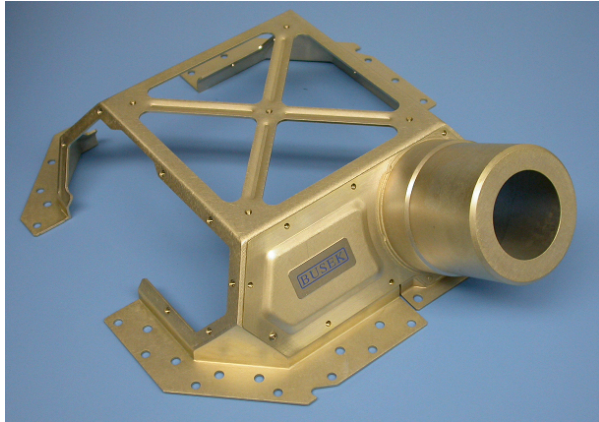
- Thruster Head (including heater)
- Microvalve (precision flow control)
- Bellows (propellant storage)
- PPU (high-voltage converters)



LISA

Flight Hardware is Being Fabricated!

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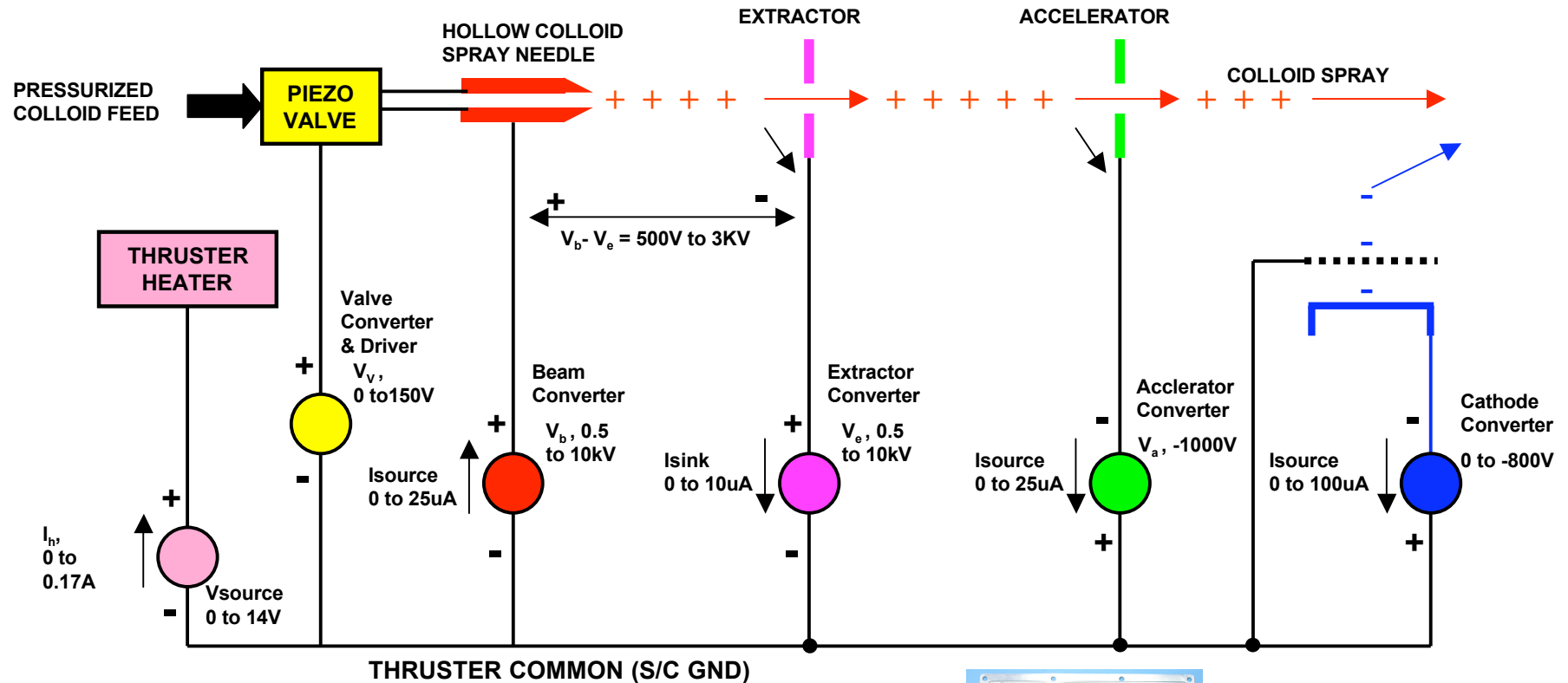


- A majority of the flight thruster parts for ST7 have been fabricated
- Inspection and acceptance of parts continues at Busek
- Completed parts include:
 - Thruster/cluster structure
 - Propellant storage bellows
 - Cathode neutralizers
 - Microvalve parts
 - High-voltage converters
- Flight hardware build will be complete by Sept. 2006; delivery to JPL set for October 2006
- Remaining parts include thruster head and bubble eliminator



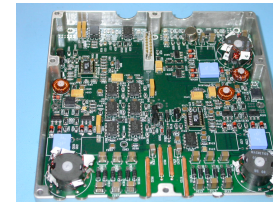
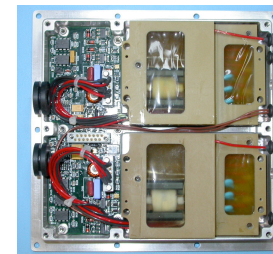
Thruster Power Processing Unit Schematic

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CONTROLLED VARIABLES: V_b , $(V_b - V_e)$, V_v , I_h , I_c

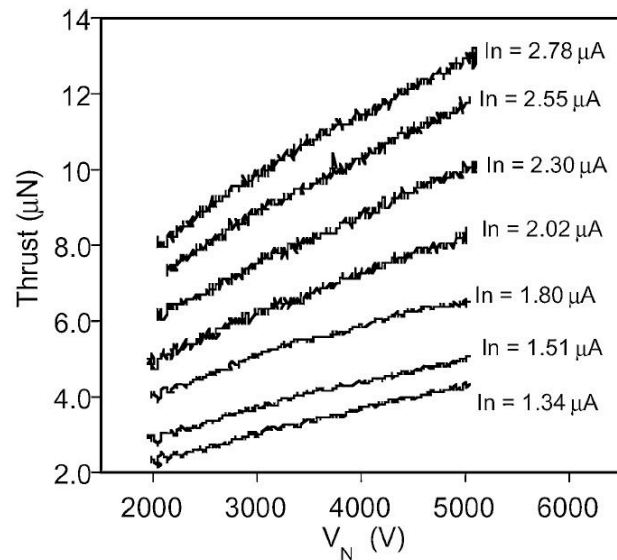
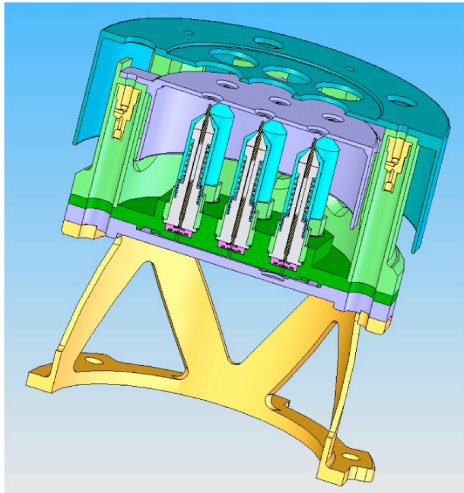
- PPU challenge is having two high voltage variable output DC-DC converters capable of providing 0.5 to 10 kV in a continuous range
- Flight hardware delivery in August 2006 by Assurance Technology Corporation (ATC)





Thruster Head and Micro-Valve Performance

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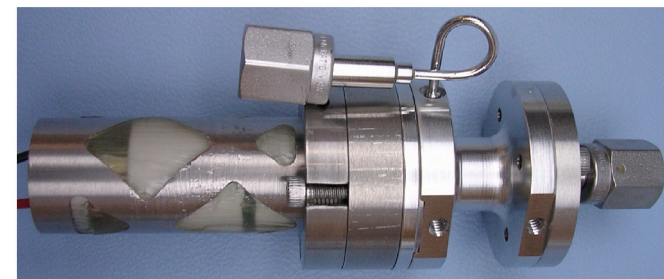
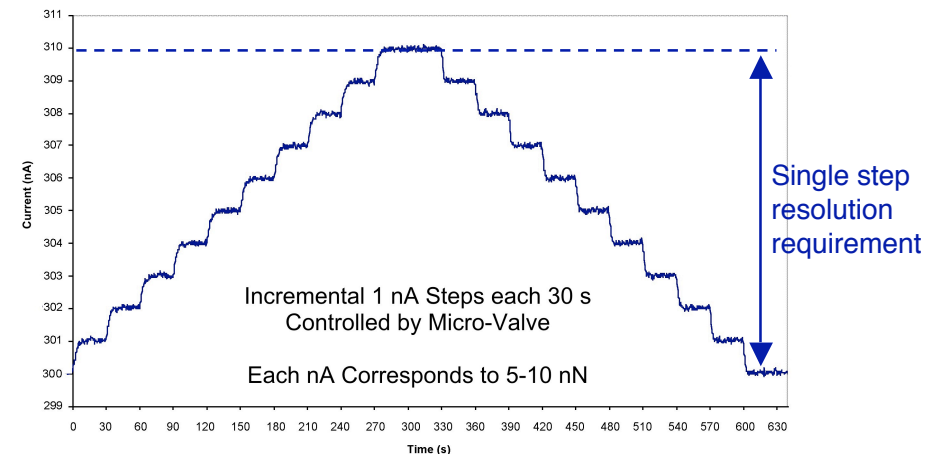
Direct thrust measurements taken at Busek from 6-needle breadboard ST7-DRS CMNT

Thruster head and microvalve meet LISA performance requirements:

- 5-30 μN with $< 0.1 \mu\text{N}$ resolution
- $< 0.1 \mu\text{N}/\sqrt{\text{Hz}}$ thrust noise

System-level performance testing at Busek will be complete by August 2006

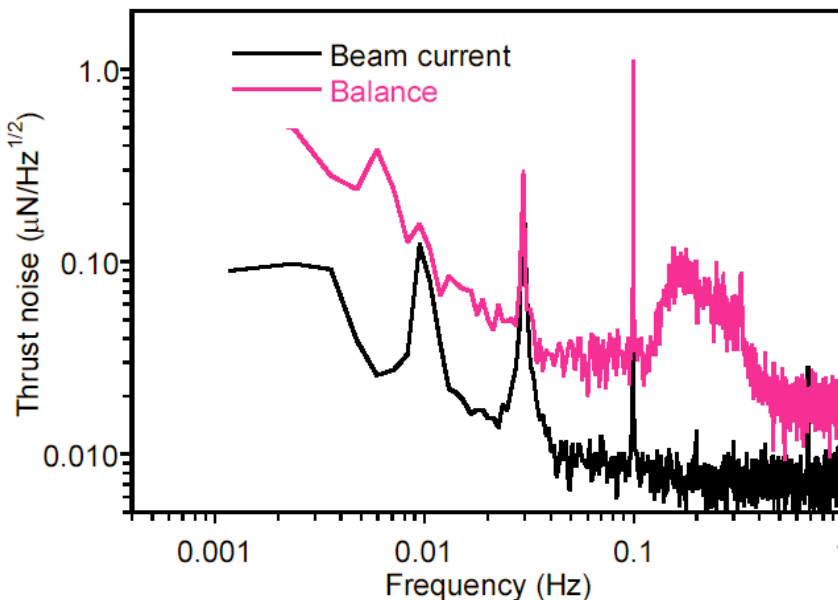
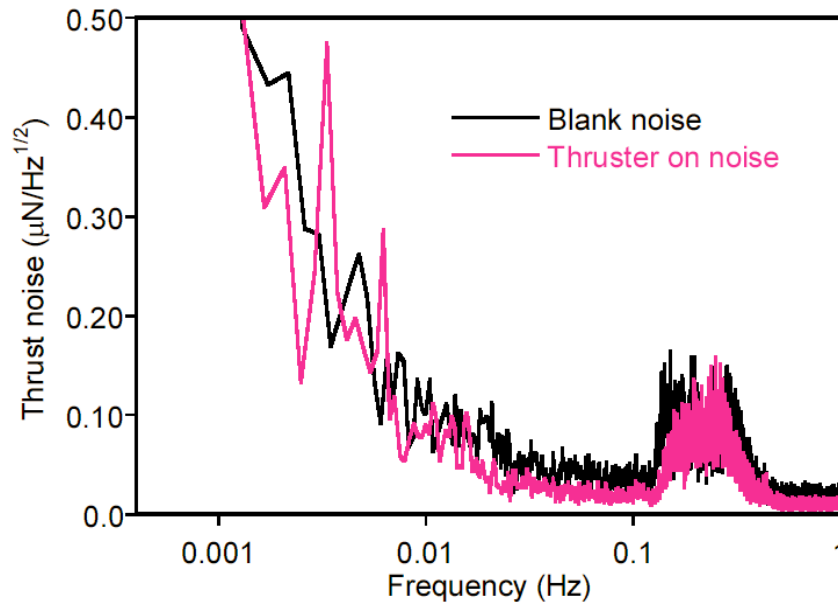
Micro-Valve Resolution



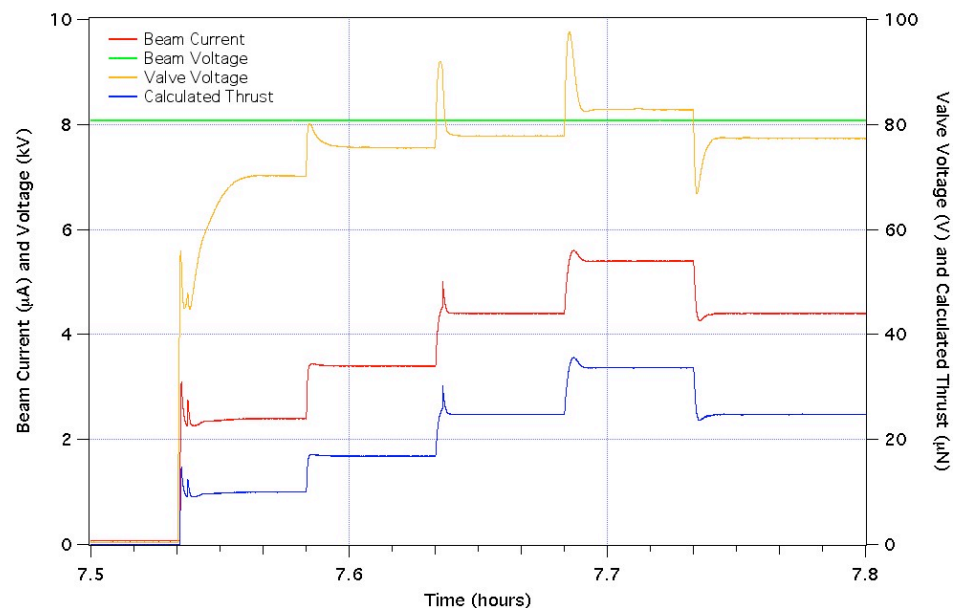


Direct Measurement of Thrust Noise

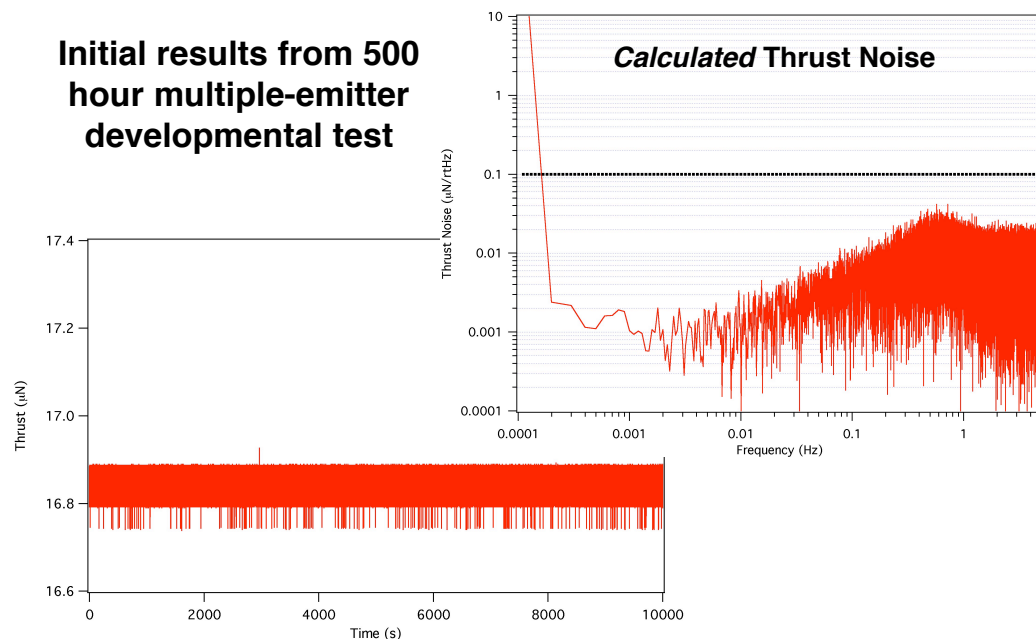
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- These results from Busek represent the best ground measurements of thrust noise taken to date (new measurements started this May, complete by August)
- Open loop measurements demonstrate that the thruster meets ST7 and LISA requirements down to 10 mHz where test facility and thrust stand noise dominate
- Measurements < 10 mHz are based on current and voltage measurements and also meet ST7 and LISA thrust noise requirements
- Thrust stand response correlates well with intentional variations of beam current (peaks on thrust noise plot)
- JPL has a thrust stand with similar resolution characteristics that will be used to verify Busek data for LISA



Initial results from 500 hour multiple-emitter developmental test



Testing experience to date:

- Single emitter tests: four >3000 hour tests completed (latest one finished at the end of April)
- Multiple-emitter tests: six >500 hour tests with complete system completed over the last 8 months

Currently focusing on multiple-emitter system level tests

- System-level tests include full thruster assembly (thruster head, microvalve, and bellows) and electronics (PPU and DCIU) all under vacuum in the same facility
- Multiple developmental designs have led to solutions for clogging, bubbles, and overspray for ST7 lifetimes
- Current >500 hours into a 3000 hour long duration test of the most recent baseline flight design

Direct thrust measurements and final development of the thrust control algorithm are ongoing in parallel



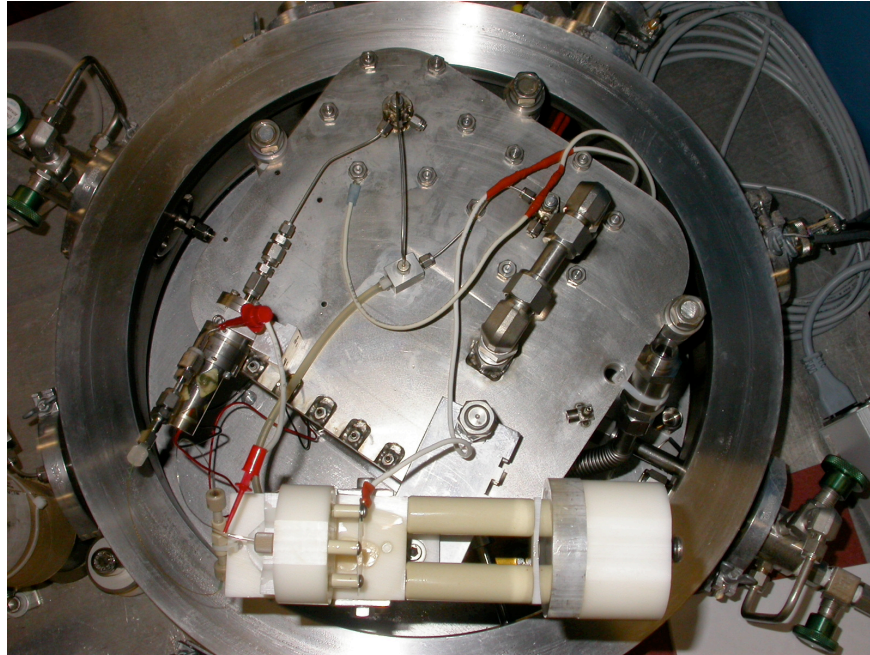
LISA

Long Duration Emitter Wear Test

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BUSEK



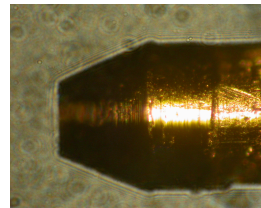
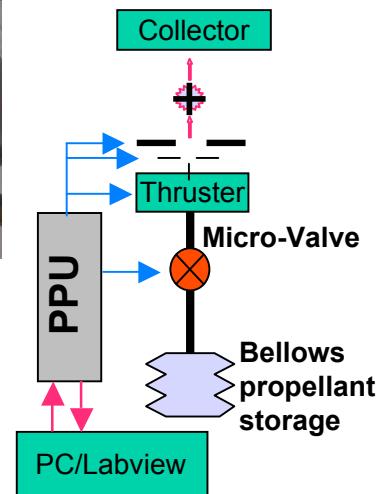
Designed to test erosion of new emitter material after initial tests of stainless steel emitters showed signs of pitting and erosion

Components:

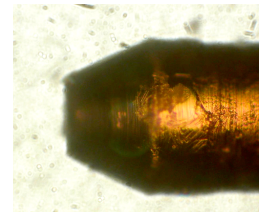
- Single electro spray capillary emitter
- Breadboard bellows, microvalve, and electronics

Results:

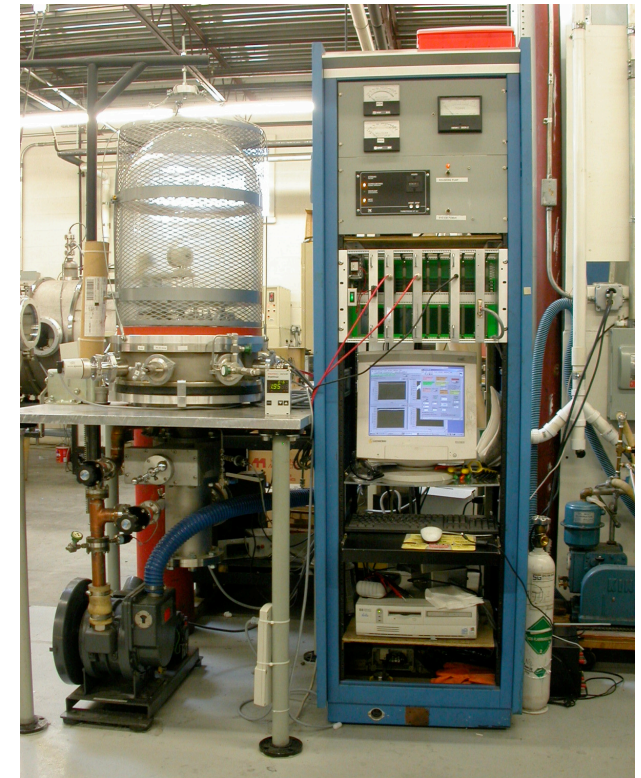
- No mechanical or electrical failure of any kind
- 3,635 hours total – test stopped voluntarily
- No degradation of emitter tip (some propellant deposits)
- Gradual valve opening to emit a constant current



Before Test



After >3300 Hours



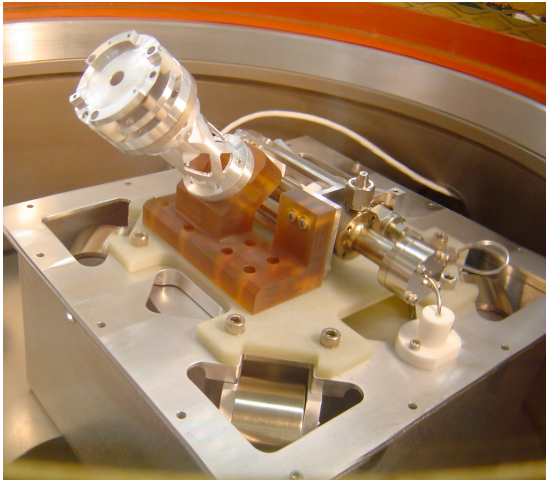
Vacuum facility and associated electronics for LDT #4



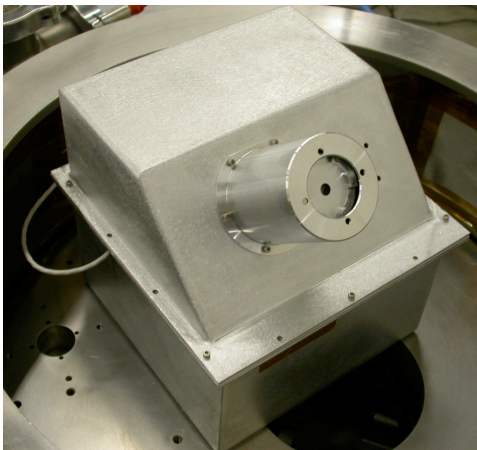
LISA

Next Lifetest Demonstrates Solution for ST7

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**Single needle
colloid thruster
system**



Objective:

- Test new emitter design
- Demonstrate 3,300 hour life (2,200 hours mission +50%) with no significant clogging

Hardware:

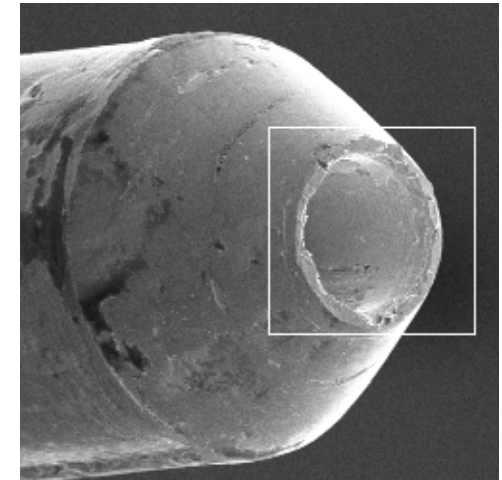
- All breadboard and EM-level hardware
- A complete system except no heater and neutralizer; controlled via LabVIEW

Results:

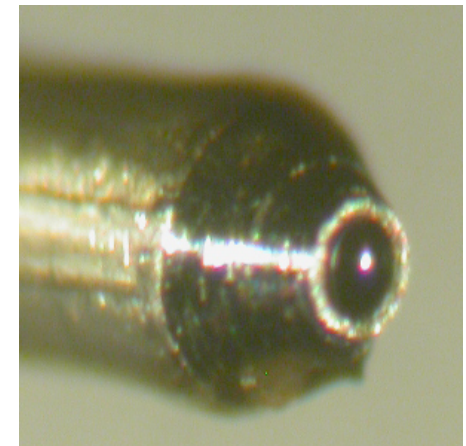
- Total duration: 3,406 hours
- Average valve voltage drift: 6 mV/hr
- Change is attributed to average lab temperature dropping by 8° C over course of nearly 5 months. 24 hour day/night cycles also noted

Conclusions:

- *No apparent change in emitter tip, no significant change in hydraulic resistance of capillary*
- *Still a potential concern for LISA; may require new emitter design or change in operation strategy*

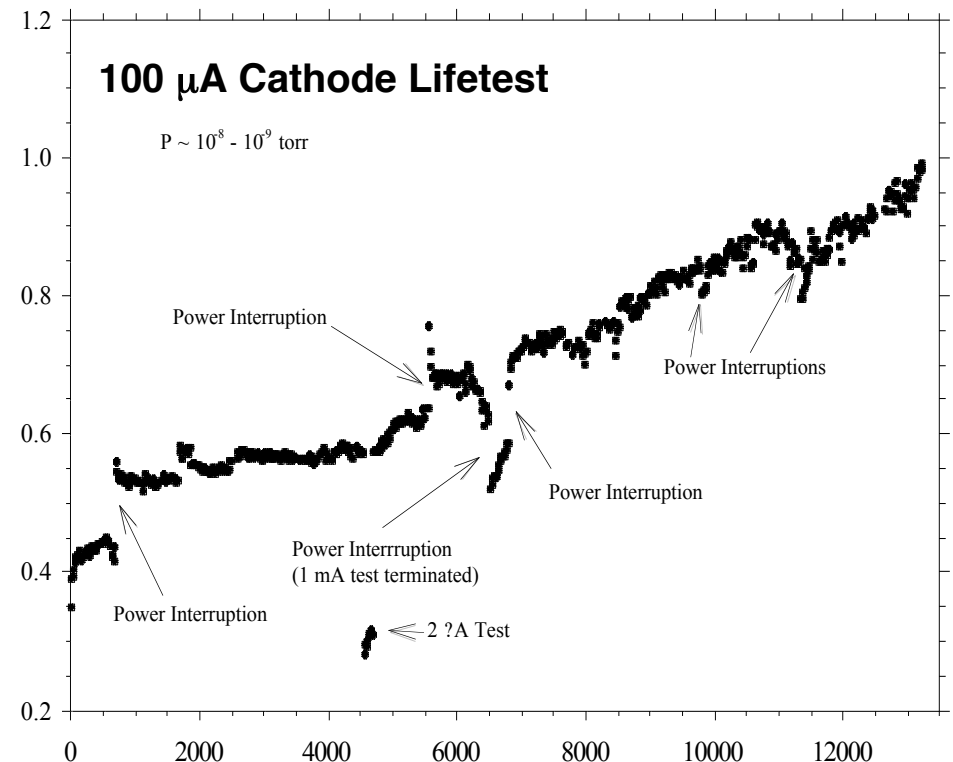


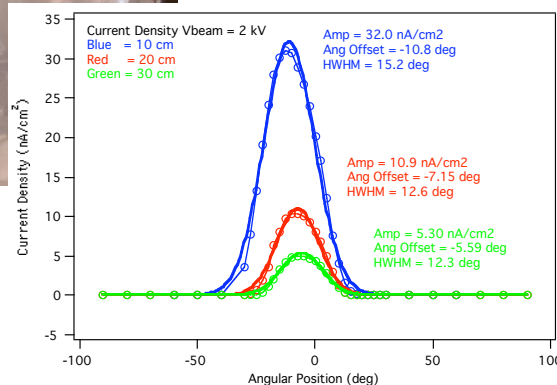
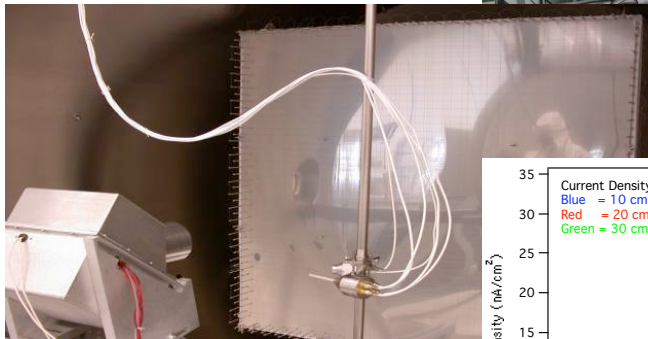
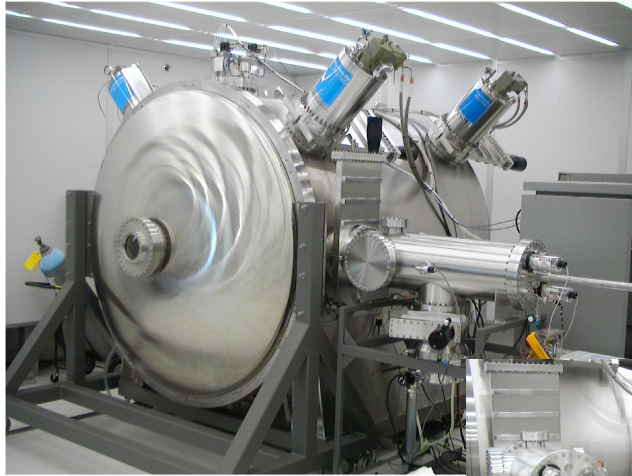
SEM photo before test






Emitter after ~3400 hours

- Field emission cathode neutralizer uses Busek-grown multi-wall carbon nanotubes
- Maximum current output more than adequate (~ 1 mA); only requires one per cluster
- Passed vibration test successfully
- Lifetest complete
 - Cathode operated at $100\ \mu\text{A}$ for 13,236 hours
- Also tested with propellant exposure and under UV light showing no degradation
- Active neutralizer in latest system-level lifetests at Busek





-  JPL Microthruster Propulsion Laboratory has already been used for multiple thruster tests
-  Laboratory includes:
 - 2m x 2m Ultra-High Vacuum (UHV) environment for testing FEEP and Colloid Microthrusters
 - Class-10 clean room environment
 - Nano-Newton Thrust Stand for performance measurement
 - Exhaust beam profiling and contamination diagnostics
 - Load-lock system for rapid turn around and in-situ thruster inspection
-  Facility is ready for long-duration unattended operation for microthruster lifetesting



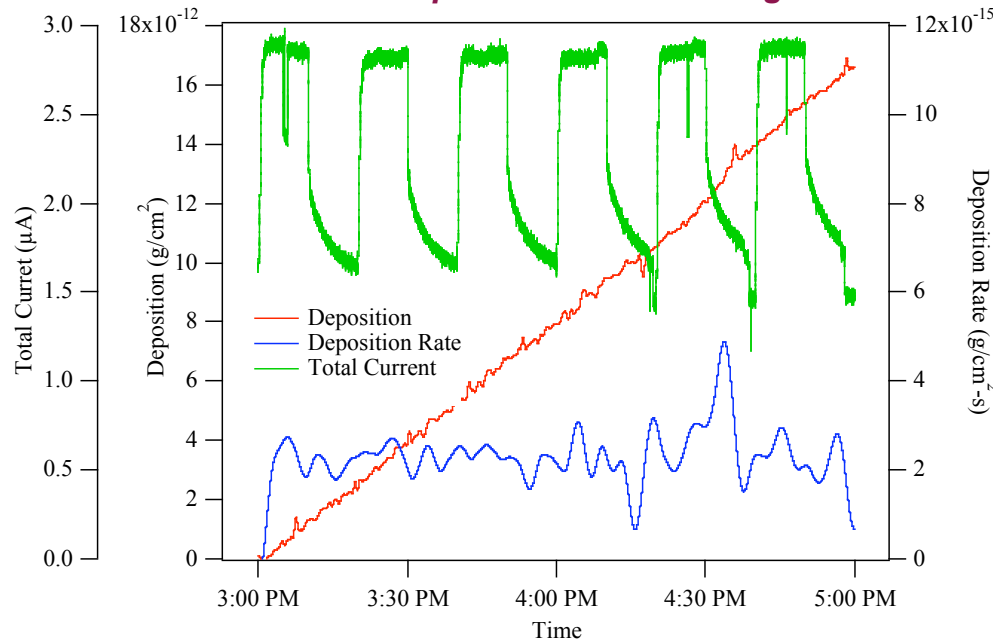
ST7-DRS Colloid Micro-Newton Thruster Meets LISA Pathfinder Contamination Requirements

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BUSEK

ST7 Mission Requirement: $13 \times 10^{-15} \text{ g/cm}^2\text{-s}$

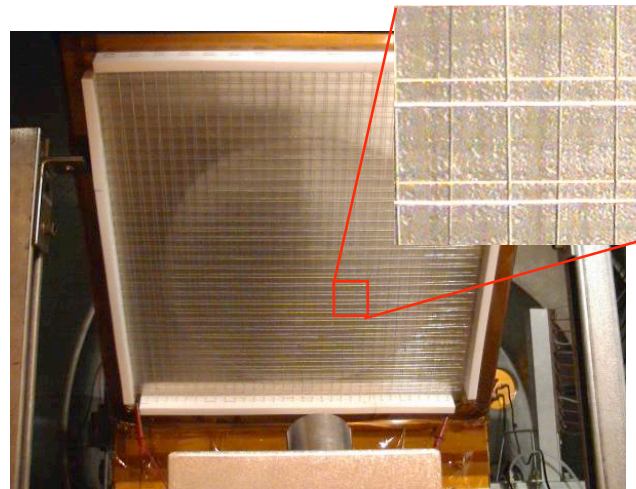
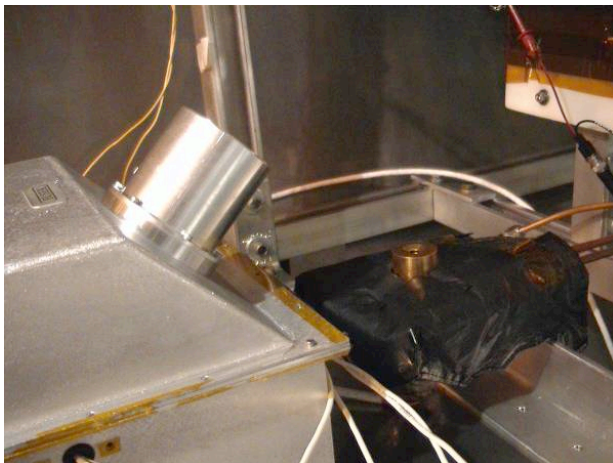


ST7-DRS Project needed a demonstration of compliance with contamination requirements for LISA Pathfinder

Requirement: $< 0.1 \mu\text{g/cm}^2$ at $> 45^\circ$ half-angle over lifetime of the mission (3 months)

Results:

- Mass deposition measurements of Colloid Thruster plumes had never been made before
- Average rate: $10^{-15} \text{ g/cm}^2\text{-s}$, producing $< 0.01 \mu\text{g/cm}^2$ over three months
- **Meets ST7 Requirements by a factor of 10**



Future Technology Needs:

- Evaluate and mitigate long-term contamination (55000 hours)
- More sensitive measurements ($\times 10$)
- Plume modeling
- Off-ramp: beam focusing

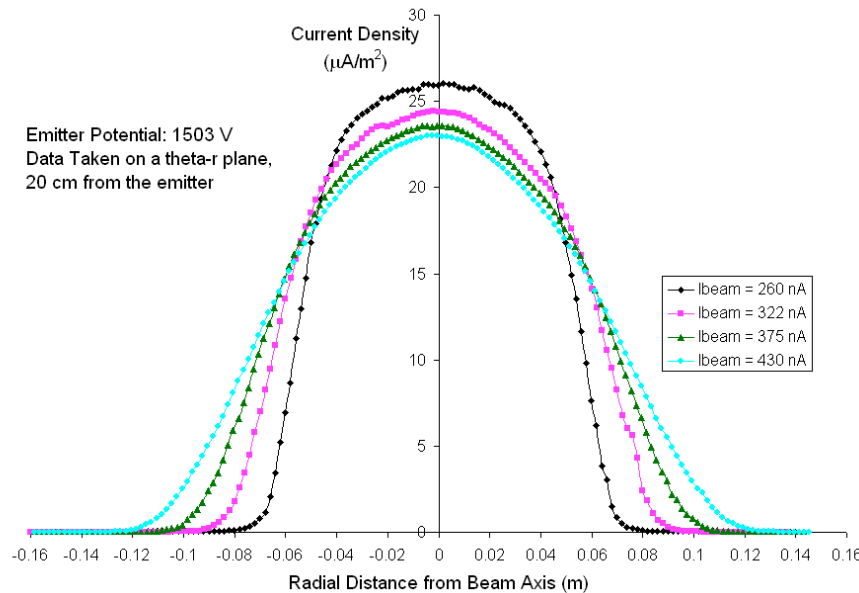


Beam Profile and Current Density Measurements in Colloid Thruster Plume

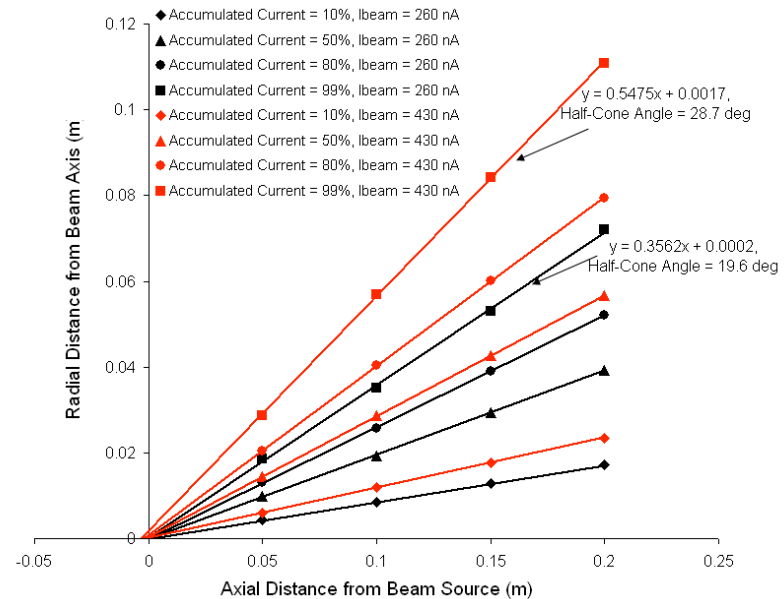
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Beam Radial Profiles for Varying Currents



Accumulated Current Envelopes



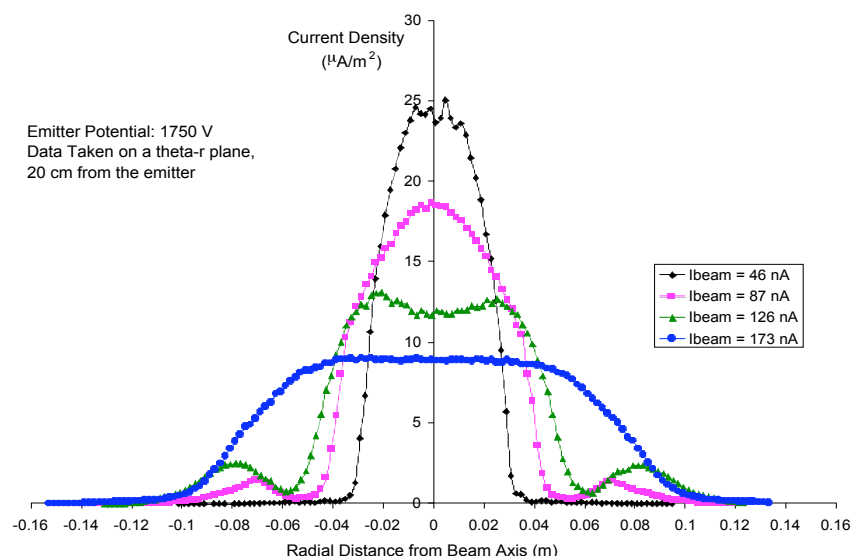
🔧 **Challenge:** Exhaust beam current density (beam divergence) determines thruster performance and contamination

🔧 **Solution:** Measure current density as a function of angle and determine current “envelops” encompassing 10%, 50%, 80%, and 99% of the total beam current

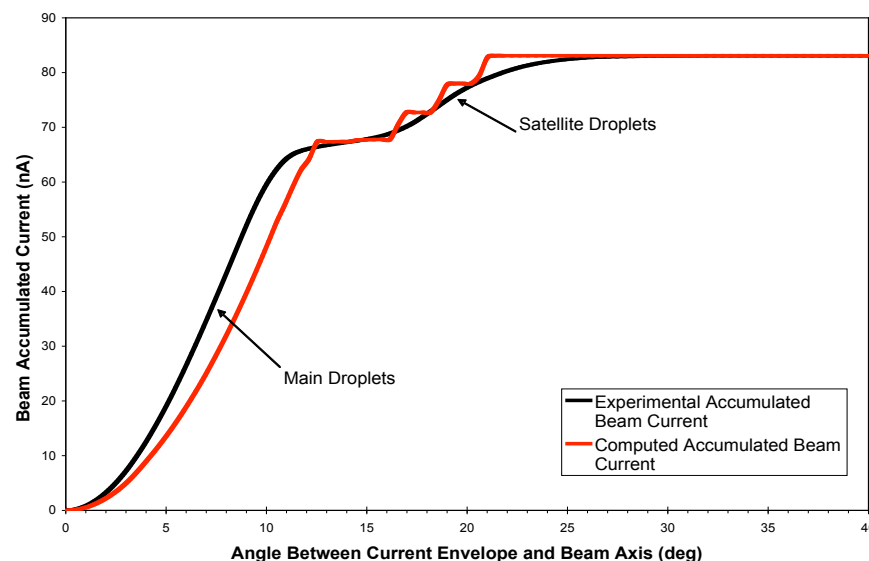
🔧 **Results:**


- Space charge forces in the beam are negligible beyond the emitter tip (1 - 2 mm)
- For nominal thrust 99% of the beam current is within a 19.6° half-angle
- For full thrust 99% of the beam current is within a 28.7° half-angle

Measured Charge Flux “Distribution” Functions



Accumulated Charge Flux “Distribution” Functions Comparison Between Experimental and Model Results



 **Challenge:** Exhaust beam is made up of both ions and droplets; we must understand where they are formed and where they go to understanding contamination and lifetime issues

 **Solution:** Develop model and verify with measurements

 **Results:**

- Model and experimental results agree well; the model is a tool for designing the geometry of the extracting and emitter electrodes and predicting contamination
- We now understand where ions and droplets are created, allowing us to predict the anion flux back to the emitter walls and estimate the deposition rate as a function of current

- 🚀 Busek is developing flight-level Colloid Microthruster Systems
 - Thruster system has gone through peer reviews, PDR, and CDR for ST7
 - Flight-level thruster components currently in fabrication
 - Multiple > 3000 hour tests have been conducted at Busek
 - Thruster testing is continuing to insure performance and reliability
 - Full flight system delivery to ST7-DRS project in October of 2006

- 🚀 JPL will continue to develop Colloid Microthruster Technology for ST7-DRS and LISA, focusing on thruster lifetime
 - Minimize changes to flight hardware development from ST7 to LISA
 - Provide verified lifetime models and > 8000 hours of continuous operation by PDR

- 🚀 Busek will be involved with LISA technology development from the beginning to the end of the program
 - Latest contract provided an ST7 thruster to JPL for testing (results to be presented at Joint Propulsion Conference in July 2006) and analysis on major lifetime issues